Department of Energy
Washington, DC 20585

SAFETY EVALUATION REPORT (SER)
RTG (Radioisotope Thermoelectric Generator) Package
Docket 94-6-9904

SUMMARY

The Richland Operations Office (RL) of the Department of Energy (DOE) with the assistance of its contractors, Westinghouse Hanford Company and Packaging Technology, Inc., has requested a DOE Certificate of Compliance (CoC) for the RTG Package. The original requested contents were the GPHS (General Purpose Heat Source) RTG and a somewhat larger generic payload. With the agreement of RL, the content authorized in Revision 0 of the CoC and confirmed in this SER is limited to just the GPHS RTG. Fissile Class III and exclusive use shipment in a semi-trailer specifically built for the RTG Package were also requested.

The EM-76 Packaging Certification Team has determined that the RTG Package design satisfies the requirements of 10 CFR Part 71 that became effective April 1, 1996, and has accordingly awarded the Certificate of Compliance with the B(U)F-85 designator. However, the SARP itself, which was prepared to document compliance with the 1983 requirements of 10 CFR Part 71, does not show compliance with the 1996 requirements of 10 CFR Part 71 in two areas as follows:

- In Chapter 3, Thermal Evaluation, the SARP demonstrates compliance with the still-air concept of the Hypothetical Accident Thermal Event of the 1983 version instead of the fire-enhanced convection concept of the 1996 version.
- In Chapter 6, Criticality, the SARP demonstrates compliance with the 2 undamaged and 1 damaged package concept of the 1983 version instead of the 3 undamaged and 1 damaged package concept of the 1996 version.

These areas must be addressed in Revision 1 of the SARP. Upon submission to the Packaging Certification Team, the SARP will be reviewed to determine that it satisfactorily documents compliance with all regulatory requirements.

In addition, the Certificate of Compliance imposes a condition not provided in the SARP which also must be addressed in Revision 1 of the SARP. The Certificate of Compliance requires the entire containment boundary of both the outer containment vessel and the inner containment vessel to pass a 1×10^{-7} std cm^3/s air leak test within the 12 months preceding a shipment. This condition is imposed in the Certificate of Compliance to satisfy the recommendation of ANSI (American National Standards Institute) N14.5 for periodic leak testing.

If the RTG Package is used for international shipments, a Certificate of Competent Authority showing compliance with the requirements of the International Atomic Energy Agency (IAEA) Safety Series No. 6 (SS 6), 1985 Edition (as amended 1990) must be obtained. The RTG Package design has not been reviewed for compliance with SS 6. Although the 1996 requirements of 10 CFR Part 71 are derived from SS 6, SS 6 has somewhat different requirements. One difference that will have to be addressed in the SARP to show compliance with SS 6 as well as the 1996 requirements of 10 CFR Part 71 is that SS 6 requires that the drop and puncture test be done in the order that produces the most damage while 10 CFR Part 71 specifies the order as drop followed by puncture. The last puncture test conducted on the RTG Package caused the impact limiter's skin to tear at a vent hole. To show compliance with SS 6, the SARP will have to show that a subsequent drop test will not cause the impact limiter to fail.

The EM-76 Packaging Certification Team has concluded that the RTG Package design complies with DOE Order 460.1, the 1996 requirements of 10 CFR Part 71, and 49 CFR Part 173. Accordingly, based on the statements and representations made in the SARP, EM-76 has awarded a Certificate of Compliance with the condition that both containment boundaries pass a periodic leak test equivalent to the acceptance leak test.

DISCUSSION

The Packaging Certification Team review of the RTG Package application follows in the order of the chapters of the SARP.

Chapter 1. Introduction and General Information

Westinghouse Hanford Company (WHC) has prepared for the U.S. Department of Energy (DOE) a Safety Analysis Report for Packaging (SARP) for the Radioisotope Thermoelectric Generator (RTG) Transportation System Package (this document is referred to as the RTG SARP). This package is a Type B(U)F packaging system used to transport an RTG or similar payload. The RTG payloads provide highly reliable power sources for use in deep space and terrestrial missions. This Safety Evaluation Report (SER) documents the review performed by the EM-76 Packaging Certification Team.

The RTG SARP provides information on two payloads: (1) a General Purpose Heat Source (GPHS) RTG payload, and (2) a generic, enveloping payload. With the agreement of RL, only the GPHS RTG payload is reviewed in this SER. The GPHS RTG contains plutonium fuel in the form of PuO_2, which is in pellet form. The payload is classified as Fissile Class III and contains sufficient quantities of plutonium to warrant the special requirements of 10 CFR 71.63 ("Special Requirements for Plutonium Shipments"). In accordance with 10 CFR Part 71 (1996 Version), Fissile Class III is replaced with a Transport Index of 100 in the Certificate of Compliance.

The package stands about 77 inches high, and has a maximum outer diameter (of the impact limiter) of 70 inches. The gross weight of each package, including payload and impact limiter, is approximately 9,300 pounds. The package, with its impact limiter in place, is mounted on its own transport skid (for shock and vibration protection of the payloads), and is equipped with an active cooling system for thermal protection of the payload. Neither the transport skid nor the cooling system are evaluated in this SER, although the cooling channels, empty of coolant, are considered to be present. The impact limiters are required for thermal protection during the hypothetical accident condition fire. The package is transported within a specially designed exclusive-use trailer.

The RTG package includes a double containment system, required by 10 CFR 71.63, for plutonium shipments. The RTG containment system consists of two independent stainless steel vessels: an inner containment vessel (ICV) and an outer containment vessel (OCV). Each containment vessel is closed via a bolted flange sealed with two elastomeric O-rings. In each case, the inner O-ring provides containment and the outer O-ring permits leak testing. Electrical feed-through assemblies are located within recessed holes in each of the OCV and ICV bases. These provide a means to continuously monitor the RTG payload during transport. Once installed, the electrical feed-through portion of the containment boundary is never broken. The electrical feed-through assemblies are leak tested with the entire containment boundary at the time of the acceptance testing and maintenance testing. The design of the containment vessels complies with Section III, Subsection NB of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code.

The RTG SARP was prepared to document compliance with the 1983 version of 10 CFR Part 71. The EM-76 reviewers have consequently used 10 CFR Part 71 (1983) as the basis for their review. In addition, a review has been made to document compliance, or the lack thereof, with the April 1, 1996, version of 10 CFR Part 71 (denoted 10 CFR Part 71 (1996)), and with IAEA Safety Series 6 (1985 version, as amended in 1990). The Acceptance Criteria sections in each chapter of this SER use 10 CFR Part 71 (1983) as the basis, and the Findings and Conclusions sections document compliance with this basis. In addition, the Findings and Conclusions sections either indicate compliance with 10 CFR 71 Part (1996) and with IAEA Safety Series 6 (1985 version, as amended in 1990) or list requirements from these documents that have not been demonstrated in the RTG SARP.

1.1 Areas of Review

This chapter of the SER discusses the review of the RTG SARP for adequacy of the description of the RTG package. Included in the review were the following items:

1. Description of the package.

   - Classification of the package as Type B(U), Type B(M), or fissile material packaging,
   - Gross weight,

- Model identification,
- Identification of the containment system,
- Specific materials of construction, weights, dimensions, and fabrication methods of:
  - receptacles,
  - non-fissile neutron absorbers or moderators,
  - internal and external structures supporting or protecting receptacles,
  - valves, sampling ports, lifting devices, and tie-down devices,
  - structural and mechanical means for the transfer and dissipation of heat,
- Identification and volumes of any receptacles containing coolant.

2. Description of the contents of the package

   - Identification and maximum radioactivity of radioactive constituents,
   - Identification and maximum quantities of fissile constituents,
   - Chemical and physical form,
   - Extent of reflection, amount and identity of non-fissile materials used as neutron absorbers or moderators, and atomic ratio of moderator to fissile constituents,
   - Maximum normal operating pressure,
   - Maximum weight,
   - Maximum amount of decay heat,
   - Identification and volumes of any coolants.

3. Operational features of the package.

1.2 Acceptance Criteria

An application for an approval under 10 CFR Part 71 must include the following information listed in §71.31(a).

1. A package description as described by §71.33.

2. A package evaluation as described by §71.35.

3. A quality assurance program as required by §71.37.

4. In the case of fissile material, an identification of the proposed fissile class.

Of these items, Reg. Guide 7.9 recommends that the package description as specified by §71.33 be included in Chapter 1 of the RTG SARP. In addition, Reg. Guide 7.9 recommends that operational features, including a discussion of the package operation, be provided in Chapter 1 of the RTG SARP.

Chapter 1 of this SER addresses those items which are described by §71.33 and/or which are recommended by Reg. Guide 7.9 to be provided in Chapter 1 of the RTG SARP. These items may actually be included in Chapter 1 of the RTG SARP, or they may have been included elsewhere in the RTG SARP.

The RTG SARP must also comply with U.S. Department of Energy Order 460.1.

1.3 Review

1.3.1 Review of Packaging Description

The RTG transportation system package is seeking classification as a Type B(U)F package. The model number for the RTG package is listed as RTG Package. The RTG containment system consists of two independent stainless steel containment vessels: an inner containment vessel (ICV) and an outer containment vessel (OCV), providing a double containment system. This is described fully in Section 1.2.1 of the RTG SARP. The packaging stands about 77 in. high, and has a maximum outer diameter (of the impact limiter) of 70 in. The gross weight of each package, including payload and limiter, is approximately 9,300 pounds. The cavity dimensions are approximately 57 in. high by 34 in. in diameter. The empty weight of the package is 9,100 pounds. Chapter 1 of the RTG SARP includes detailed drawings which provide dimensions, some material specifications, and some fabrication information for packaging components. Sufficient information is provided either in the drawings or elsewhere in the RTG SARP. Mechanical properties of materials are provided in Chapter 2 of the RTG SARP.

No neutron-absorbing materials other than the packaging steel walls are required for compliance with 10 CFR Part 71. However, for normal handling purposes, a water-glycol solution is used in the OCV cooling jacket, which acts also as a neutron absorber to reduce worker radiation exposure. The cooling jacket is assumed to be empty of coolant for the purposes of the review.

A shipping rack is used to assist in attaching the RTG payloads to the ICV base for restraint during normal shipping and handling operations. The shipping rack is fastened to the ICV base and is designed to remain in place during a hypothetical accident condition (HAC) drop to prevent heat-generating payload debris from reaching the proximity of the ICV O-ring seal area. The payload attachment bolts and payload itself are not expected to survive the HAC.

The containment vessels are designed to withstand all pressure buildups that may occur during the normal conditions of transport (NCT) and HAC. No pressure relief systems for the containment boundaries are provided.

The containment vessels are each equipped with a helium fill (primary vent) port; the ICV also has a secondary port. These ports are used to establish a pressurized helium atmosphere inside each containment boundary at the time of loading. In addition, each containment vessel is equipped with a leakage rate test port which accesses the region outside the containment O-rings in order to perform leakage testing prior to shipment.

Lifting the package is accomplished via three of the twenty-four OCV cooling fins, which double as lifting lugs. The ICV is lifted with a single lift point in the ICV head. Since the package is secured to its transport skid with a pair of tie-down straps that pass over the top of the locally reinforced OCV at right angles to one another, there are no tie-down devices that are an integral part of the packaging. The package is transported within an exclusive-use trailer, designed specifically for transport of the RTG package.

Means of heat dissipation include:

1. high emissivity surface treatments (black paint) on the inner and outer surfaces of the ICV and the inner surface of the OCV,

2. a dimensionally controlled gap between the ICV and the OCV bells, which is not necessary to satisfy the requirements of 10 CFR Part 71,

3. a helium cover gas within the containment vessel cavities, and

4. an active cooling system (see below).

Active cooling for the payload is accomplished by circulating a 70% water/30% propylene glycol mixture through the package OCV cooling jacket. The system is described in Section 1.2.2 of the RTG SARP and is intended to be a completely redundant system. The purpose of the cooling system is to provide operational protection of the payload during transport. The cooling system is not required to be active for the RTG package to comply with 10 CFR Part 71 and is not reviewed further in this SER. The empty cooling channels located on the exterior of the OCV are included in the structural and thermal evaluations because they are an integral part of the OCV.

1.3.2 Review of Contents Description

The RTG SARP provides information on two payloads: (1) a General Purpose Heat Source (GPHS) RTG payload, and (2) a generic, enveloping payload. With the agreement of RL, only the GPHS RTG payload is reviewed in this SER.

The payload is classified as Fissile Class III and contains sufficient quantities of plutonium to warrant the special requirements of 10 CFR 71.63 ("Special Requirements for Plutonium Shipments"). The GPHS RTG contains plutonium fuel in the form of PuO_2, which is sintered into pellets. Each pellet is a right circular cylinder clad with an iridium shell which contains a vent allowing the helium produced from ^{238}Pu decay to escape. The pellets are grouped by twos into graphite impact shells, which are in turn enclosed in a reentry member called an aeroshell. A series of tests was performed by the applicant to verify the aeroshell's structural integrity. No credit is taken for the iridium shell's and aeroshell's contributions to the containment of radioactive material in the RTG package.

Identification and maximum radioactivity of radioactive constituents is provided in Table 1.2.3-3. Identification and maximum quantities of fissile constituents is provided in Table 1.2.3-4. The RTG package content is limited to one GPHS RTG. The GPHS RTG shall contain no more than 11.3 kg of PuO_2 with a total activity of 1.42 x 10^5 Ci (5.3 x 10^{15} Bq). The composition of the plutonium shall fall within the radioactive isotopic composition shown in Table 1-1 below.

Table 1-1. Radioactive Constituents

Isotope	Weight % of Total Pu
^{236}Pu	≤0.0001
^{238}Pu	80 to 86
^{239}Pu	≤20

The total fissile material (^{238}Pu, ^{239}Pu, and ^{241}Pu) is limited to 9.96 kg per GPHS RTG. The maximum thermal generation rate of the GPHS RTG shall not exceed 4,500 W. The maximum neutron emission rate for a single GPHS RTG shall not exceed 6,000 n/s-g ^{238}Pu (5.14 x 10^7 n/s per package). No specific neutron reflectors, neutron absorbers, or neutron moderators are included in the package design.

Maximum normal operating pressure is 30 psia in the ICV and 30 psia in the OCV. The maximum GPHS RTG internal heat load is 4,500 W.

Maximum weight of the GPHS RTG is 123.1 pounds, excluding the interface hardware. Including this hardware brings the total weight of the GPHS RTG to 200 pounds.

1.3.3 Review of Operational Features of the Package

The operational features of the RTG package are summarized in Section 1.2.2 of the RTG SARP, and are fully described in Chapter 7 of the RTG SARP.

1.4 Findings and Conclusions

A review of Chapter 1, General Information, of the RTG SARP was performed for the GPHS RTG contents only. The acceptance criteria defined by Section 1.2 of this SER have been satisfied.

Chapter 2. Structural Evaluation

2.1 Areas of Review

The RTG SARP Chapter 2 was reviewed for adequacy of the structural design features of the RTG Package. Included in the review were the following:

1. Structural design criteria and design features:

- Standards used during fabrication and processing,
- Design loadings and criteria related to maintaining containment, shielding, and subcriticality,
- Lifting and tie-down components.

2. Material properties and specifications:

   - Acceptability of material specifications,
   - Fracture resistance of containment and safety-related materials,
   - Packaging fasteners and welds.

3. Methods and bases for determining structural loads or test conditions applied to safety-related components:

   - Identification of safety-related structural components,
   - Maintenance of containment, shielding, and subcriticality functions,
   - Adequacy of analytical methods and cited test results.

2.2 Acceptance Criteria

2.2.1 Establishment of Requirements

The following sections of 10 CFR Part 71 establish requirements for the listed categories:

1. The evaluation of a package [§71.31].

2. A package description [§71.33].

3. Fabrication and processing standards and quality assurance implementation provisions [§71.37].

4. General structural standards and criteria [§71.43].

5. Lifting and tie-down standards [§71.45].

6. Structural damage resulting from NCT [§71.71] or during HAC [§71.73].

2.2.2 Package Structural Design

Package structural design is acceptable if it can be shown that the following conditions apply:

1. The package was designed using methods and criteria appropriate for the behavior and function of the design consistent with prevailing industrial codes, standards, and practices for structures and materials.

2. There are no structural or material effects that unacceptably degrade containment, shielding, and subcriticality functions of the package.

2.3 Review Procedure

The RTG SARP includes information essential for structural evaluation, such as engineering drawings; the gross package weight; the weight of the contents; the center of gravity; and the maximum operating pressures and temperatures. Of particular importance from a structural evaluation view are the behavior of the following RTG packaging components: (1) the inner and outer containment vessels (ICV and OCV), (2) the impact limiter, (3) the ICV and OCV closure bolts, the limiter attachment bolts, and the limiter skin welds, (4) the electrial feed-through, and (5) the containment seals.

The ICV and OCV design of the RTG package complies with §71.63 which requires double containment for packages containing more than 20 Ci plutonium. Section 1.2.2 of the RTG SARP describes the method of closure of the containment vessels: each vessel is a stainless steel flanged bell with a bolted-on flat stainless base plate. Each of the containment vessels is closed with 24 bolts. The Packaging Certification Team concurs that the method meets positive closure requirements [§71.43]. The Team also finds that the package design meets the remainder of the §71.43 requirements; namely, the package materials and contents have no adverse chemical and galvanic reactions, and all valves are protected against unauthorized operations (RTG SARP Sections 2.4.4 and 2.4.2).

RTG SARP Sections 1.2.1 and 2.5.1 describe the devices for lifting the individual containment vessels and the complete package. Based on the stress analyses presented in RTG SARP Sections 2.5.1.1 and 2.5.1.2, the Packaging Certification Team determined that the lifting devices meet the stress criteria requirements [§71.75]. The Team also determine that the tie-down requirements [§71.45] are met by the tie-down method which is described in RTG SARP Sections 1.2.1 and 2.5.2 and analyzed in Sections 2.5.2.1 and 2.5.2.2.

Water inleakage and gross deformation of the containment vessels are not detrimental to the subcriticality of the fissile contents; therefore, the containment vessels need not prevent water inleakage or maintain their original geometry. However, the RTG containment design must: (1) contain the contents, and (2) provide shielding from the radiation of the contents. Structural evaluations of the RTG package are based on the package's ability to meet these goals in both the Normal Conditions of Transport (NCT) and the Hypothetical Accident Conditions (HAC) [§71.71 and §71.73].

The evaluations for NCT were accomplished by the applicant via tests in the cases of free drop and analyses in the cases of heat, cold, reduced external pressure, increased external pressure, vibration, water spray, compression, and penetration. The corner drop [§71.71(c)(8)] is not applicable to this package because the package is not fabricated from the specified materials. The corner drop [§71.71(c)(7)] preceding the free drop is also not applicable to this package because the RTG package is not a Fissile Class II package. The evaluations for HAC were accomplished by the applicant via tests in the cases of free drop and puncture, and by analyses in the cases of fire and immersions. The crush condition is not applicable to the RTG package, because the package weight exceeds 500 kg.

The RTG SARP summarizes the conclusions for NCT in Section 2.6 and details the analyses and tests results in Sections 2.6.1–2.6.10 of the RTG SARP. The analyses show that the containment vessel design complies with the stress criteria of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code Section III, Subsection NB (for the design and construction of nuclear power pressure vessels). The NCT free-drop test results have demonstrated that the containment vessels cannot be seriously deformed by impact under the NCT. Based on the presented analysis and test results, the Packaging Certification Team considers the containment vessel design adequate. The Team, however, finds that the fabrication of the RTG containment vessels does not meet ASME Section III, Subsection NB, Article N-2500 requirements. This article requires a 100% Non-Destructive Examination (NDE) of the base metal of containment vessels. On the contrary, no NDE other than visual inspection will be performed for the RTG vessel material. Nonetheless, the Packaging Certification Team determined that NDE of the base metal is not essential for the RTG containment vessels because: (1) the strength of the very ductile vessel material (304L stainless steel) is not likely to be affected significantly by material flaws, and (2) the planned hydrostatic and helium leak tests of the vessels in conjunction with the material certification traceability should provide adequate quality assurance of the containment vessel material.

The RTG SARP summarizes the conclusions for HAC in Section 2.7 and the supporting test and analysis results in Sections 2.7.1 through 2.7.6. Additional details of the analyses and tests are given in Appendices 2.10.6 through 2.10.15. The Packaging Certification Team finds that the package maintains acceptable containment and shielding under the HAC. The finding is based on the following results observed in the final series of the certification free drop and puncture tests: (1) no cracks, fracture, rupture, and collapse of the containment vessels; (2) no unacceptable deformation and rupture of the impact limiter; (3) no significant loosening of the containment vessel's closure bolts; (4) no rupture of the impact limiter attachment bolts. The Packaging Certification Team finding is also based on the analysis results. During the fire, (1) the containment seal temperatures stay within the permissible operating temperature range of the seals; and (2) the bolted containment closure can maintain leaktight compression of the containment seals. During the 50-ft immersion, the containment vessels will not collapse under the hydrostatic pressure.

Based on the general criteria described in Section 2.1 of this report, the Packaging Certification Team finds the methods used for the test and analysis of the RTG package acceptable. The Team also finds that the cumulative damage effects of the HAC on the package are adequately addressed in the tests and analyses. The Team has verified some key results by conducting independent simplified confirmatory analyses including using the SCANS computer program [Gerhard et al, 1991]. In the free drop and puncture certification tests, the Team was given opportunities to evaluate the test plan before testing. The Team also witnessed the testing and made independent assessments of the test results. The initial design of the ICV, closure bolts, the impact limiter skin welds and attachment bolts were marginal for the HAC. The certification test plan was able to reveal the design weaknesses which have been corrected in the final design. The electrical feed-through, which was initially considered a possible weakness in the containment system, turned out to be a dependable component; visual inspections and leak tests after HAC free drop and puncture tests did not reveal any weakness of the component.

2.4 Findings and Conclusions

The applicant's structural evaluation, as confirmed by the Packaging Certification Team, demonstrates that the package design satisfies the applicable requirements for structures in 10 CFR Part 71 (1983) as defined in Section 2.2 (Acceptance Criteria) of this report. The RTG SARP demonstrated compliance with 10 CFR Part 71 (1996). The RTG SARP would also have demonstrated compliance with IAEA Safety Series No. 6 (1985 version, as amended 1990), if it had been shown that the one sequence of HAC free drop and puncture conditions evaluated in the SARP is the worst sequence.

Chapter 3. Thermal Evaluation

3.1 Areas of Review

The RTG SARP Chapter 3 was reviewed for adequacy of the thermal design features of the RTG package. Included in the review was the following:

1. Thermal design features and design criteria,
   - Design features,
   - Design criteria,
2. Thermal properties of materials,
   - Completeness,
   - Accuracy,
3. Thermal specifications of the packaging components,
   - Energy sources and/or sinks,
4. Thermal evaluation of normal transport conditions,
   - Thermal modeling adequacy,
   - Thermal test adequacy,
5. Thermal evaluation of hypothetical accident conditions,
   - Thermal modeling adequacy,
   - Thermal test adequacy.

3.2 Acceptance Criteria

3.2.1 NCT Thermal Environments

A package must be designed to stay within the established temperature limits when exposed to the NCT thermal environments, [§71.4] and [§71.71]:

1. Evaluated at the maximum normal operating pressure [§71.4],
2. Loaded package (with radioactive contents) at the most unfavorable ambient temperature conditions between -20°C (-29°F) and 38°C (100°F) in still air with no solar insolation [§71.71(b)],
3. Loaded package at an ambient temperature of 38°C (100°F) in still air with regulatory-defined solar insolation and an empty package (no radioactive contents) at -40°C (-40°F) in still air with no solar insolation [§71.71(c)].

3.2.2 HAC Structural and Fire-Caused Thermal Environments

A package must be designed to retain required containment, shielding, and criticality control functions when exposed to the HAC structural and fire-caused thermal environments [§71.4] and [§71.73]:

1. Loaded package with prior cumulative structural damage caused by free drop [§71.73(c)(1) and (c)(2)],
2. Fire event initiated at the maximum normal operating pressure [§71.4] and from the most unfavorable thermal equilibrium conditions at an ambient temperature between -20°C (-29°F) and 38°C (100°F) in still air with no solar insolation [§71.71(b)] and [§71.73(b)].

Fire event thermal conditions are:

1. Complete envelopment of the package, with a minimum surface emissivity of 0.8, in an environment of minimum temperature of 800°C or 1475°F and a minimum emissivity of 0.9, for a period of at least 30 minutes,
2. Followed by an extended cool-down period in still air with no supplemental cooling and with solar insolation optional during cooldown until all package temperatures are decreasing,
3. During the cool down period, any combustion of package contents is permitted to continue to completion [§71.73(b.3)],
4. Following completion of the fire event, the package must prove to be water-tight after eight hours of immersion at a depth of 0.9 m (3 feet) [§71.73(b.4)].

Package thermal design is deemed acceptable if it can be shown that:

1. Analytical and/or actual test thermal behaviors of the package are consistent with NCT and HAC requirements as defined in §71.71 and §71.73.

2. There are no unacceptable adverse thermal effects on the containment, shielding, and criticality control functions of the package.

3.3 Review Procedures

The applicant described the RTG packaging components including those that control the package thermal and containment environment and those detailing the RTG packaging contents. These are shown in Figures 1.2.1-1, 1.2.3-1, and 1.2.3-2 of the RTG SARP. These components are described in sufficient detail in Chapters 1, 2, and 3 of the RTG SARP to enable detailed thermal models to be generated, satisfying such requirements in 10 CFR Part 71.

The required thermal properties for all materials used in the fabrication of the RTG packaging were presented in Tables 3.2-1 through 3.2-5 in Section 3.2 of the RTG SARP. These property tables were reviewed by the Packaging Certification Team and determined to be acceptable in both detail and accuracy.

There were several significant thermal design criteria and features considered in the review:

1. Several conservative assumptions were included in the applicant's thermal modeling of HAC, particularly during the HAC fire event,

2. The ability of the RTG package to maintain double containment leak tightness throughout all regulatory-defined structural and thermal environments during both NCT and HAC,

3. The primary design features that are intended to protect the seal regions of the two nested containment vessels from unacceptable structural damage and overheating, which are:

   - the integral impact limiter attached to the OCV, which is filled with polyurethane foam, provides effective thermal insulation for the O-ring seal areas of both the OCV and the ICV,
   - the RTG package OCV side wall, with the integral water-cooling jacket, provides a local and effective thermal radiation barrier as an aid in alleviating fire-induced heat transfer to the O-ring seal areas, even though the cooling system is inactive and empty of coolant.

The applicant performed thermal evaluations for the NCT [§71.71] and HAC [§71.73] conditions using the Systems Improved Numerical Differencing Analyzer (SINDA) code [Martin Marietta 1987]. The model included a qualified (configuration-controlled) representation of the RTG contents of the package [see ED-91-001]. In addition, several NCT-condition thermal tests were performed on simulated packages and contents [see ED-91-005, ED-91-00X, and ED-91-009] and the results of a portion of these tests were used to calibrate sections of the SINDA code thermal models.

The maximum heat loading for the RTG package contents is defined as 4,500 W in Sections 1.2.3 and 3.1 of the RTG SARP. A range of SINDA cases for specified conditions during NCT was analyzed by the applicant for temperatures ranging from -40°C (-40°F) to 38°C (100°F) in still air, with and without solar insolation (with and without externally applied thermal load). (The package includes a cooling circuit which was operational in some of the cases, but which was not operating and was empty of coolant for both the NCT- and HAC-specified conditions.) The applicant did perform thermal evaluations for all NCT thermal conditions. The case involving solar insolation at 100°F proved to be the NCT worst case. The results for this worst case and several of the other cases were reported in Section 3.4 of the RTG SARP. The temperatures for the worst case results also were partially reported in Sections 2.6 and 2.10.7 of the RTG SARP, and are summarized in Table 3-1 of this report.

Table 3-1. Results of the Applicant Analysis for Worst-Case NCT Conditions (Solar Insolation at 100°F)

RTG Package Component	Calculated Maximum Temperature (°F)
OCV Dished Head	267
OCV Sidewall	284
ICV Dished Head	338
ICV Sidewall	329
OCV Baseplate	220
ICV Baseplate	222
OCV Seal Region	210
ICV Seal Region	219

Confirmatory calculations of the temperatures for these components verify that the Table 3-1 results were reasonable and conservative. The HAC regulatory conditions [§71.73] were met primarily by using analyses involving a series of SINDA thermal sub models that incorporated the following:

1. Bounding approximations of the actual crush damage to the impact limiter caused by the NCT and HAC [§71.71 and 73] sets of required free drop tests.

2. Modeled variations on severe damage to the GPHS RTG module (the package contents).

In addition, reference was made to extensive and documented manufacturer fire tests describing the thermal insulating capacity and mechanical stability of the impact limiter polyurethane foam and its burned char (see "LAST-A-FOAM FR-3700 for Crash & Fire Protection of Nuclear Material Shipping Containers"). Highlights of this report are presented in Section 3.5.1.2 of the RTG SARP, with greater detail on the polyurethane foam fire behavior presented in Section 3.6.3. As added conservative measures, the following assumptions were incorporated into the SINDA thermal models of the impact limiter polyurethane foam for HAC fire conditions:

1. The outer polyurethane foam nodes in the impact limiter (approximately the outer 2 inches; see Figure 3.4.1-2 of the RTG SARP) were assumed to disappear instantly at the start of the HAC fire.

2. Any remaining polyurethane foam node was replaced by air (instead of charring) upon reaching a temperature of 400°F, which permitted direct thermal radiation to the remaining polyurethane foam nodes from the fire-heated impact limiter liner.

As noted above, the RTG package thermal models included HAC damage to the impact limiter. The corner-drop damage seen in Figures 2.10.15.4.3-8 to 14 of the RTG SARP was closely modeled as was the side-drop damage shown in Figure 2.10.15.4.3-20 of the RTG SARP. The latter proved to be the worst-case thermal condition. These modeled conditions are shown in Figures 3.5.2-1 to 3 of the RTG SARP.

In addition, severe damage to the GPHS RTG module was modeled in several ways with the worst-case thermal condition being a combined tip-over and total loss of integrity of the module with all 18 GPHS units piled to one side on the shipping rack located at the bottom of the ICV, as shown in Figure 3.5.2-6 of the RTG SARP.

Six different HAC conditions were evaluated involving combinations of impact limiter damage and assumed GPHS RTG module damage, as listed in Table 3.5-1 of the RTG SARP. The input to the basic SINDA thermal model is presented in Section 3.6.7 of the RTG SARP, and listings of the outputs for all of the SINDA runs are presented in Sections 3.6.4 (NCT) and 3.6.5 (HAC). The temperatures for the worst-case HAC results also were partially reported in Sections 2.7 and 2.10.7 of the RTG SARP, and are summarized in Table 3-2 of this report.

Table 3-2. Results of the Applicant Analysis for Worst-Case HAC Conditions (Damage as Stated in Case 5, Table 3.5-1 of the RTG SARP)

RTG Package Component	Calculated Maximum Temperature (°F)
OCV Dished Head	1231
OCV Sidewall	933
ICV Dished Head	1115
ICV Sidewall	864
OCV Baseplate	310
ICV Baseplate	328
OCV Seal Region	325
ICV Seal Region	360

Confirming calculations of the temperatures for these components verify that the Table 3-2 results were reasonable and conservative.

Thermal performance tests were successfully completed by the applicant on O-rings of the same composition (butyl rubber) as designated for use in the RTG package and in nearly the same O-ring seal geometry. The worst condition test was near, but still above, the calculated peak HAC temperatures of the O-rings – an initial 380°F 24-hour test directly followed by a 350°F test lasting 144 hours versus the calculated temperature of 360°F which lasted for much less than 24 hours. The details of these tests are described in Section 2.10.6 of the RTG SARP and in Section 4.3 of this SER.

The completed NCT and HAC analyses and tests reported in the RTG SARP demonstrated that:

1. The impact limiter would remain in place throughout all required NCT and HAC free-drop tests [§71.71 and 73].

2. The impact limiter was effective as a thermal insulator and that the thermal modeling of the impact limiter was conservative.

3. The duration and magnitude of the calculated peak temperatures in the package regions containing the O-ring seals were within the operating time-temperature envelope of the O-rings as demonstrated by test.

4. The containment leak tightness was demonstrated following the completion of all required NCT and HAC free-drop tests.

Based on these considerations, the Packaging Certification Team concludes that the RTG package has met and exceeded the required containment, shielding, and criticality control functional goals imposed by both the NCT [§71.71] and the HAC [§71.73] thermal environments.

3.4 Findings and Conclusions

The applicant's thermal tests and analyses, as confirmed by the Packaging Certification Team, demonstrate that the package design satisfies the applicable requirements for thermal evaluation in 10 CFR Part 71 (1983), as defined in Section 3.2 (Acceptance Criteria) of this report.

Demonstration that the package satisfies the thermal requirements of §10 CFR 71.73 (1996) was not presented in the RTG SARP: The fire heat flux was based on the still-air concept of §10 CFR Part 71 (1983) instead of the fire-enhanced convection concept of §10 CFR Part 71 (1996). Also, the RTG SARP did not demonstrate compliance with one thermal aspect of IAEA Safety Series 6 paragraph 546 (1985 version, as amended in 1990): the solar insolation used was 3.1% lower than the maximum required value for the IAEA regulation.

Chapter 4. Containment

4.1 Areas of Review

Chapter 4 of the RTG SARP was reviewed for adequacy of the containment design features of the RTG packaging. Included in the review were the following:

1. Containment design features and design criteria,
   - Double containment (two nested, but completely separate, containment vessels),
   - Each containment vessel must be shown to be leak-tight per ANSI N14.5-1987 in addition to preventing loss of contents,

2. Containment boundary,
   - Containment boundary description,
   - Security against unauthorized entry,

3. Allowable release rate acceptance criteria during
   - Normal transport conditions,
   - Hypothetical accident conditions.

4.2 Acceptance Criteria

4.2.1 Containment Penetrations and Standards

Containment penetrations and basic standards must be identified and must meet the requirements of 10 CFR 71.43:

1. The outside of a package must have a design feature that, when intact, is evidence that unauthorized entry has not occurred,

2. The containment system must be securely closed by a positive fastening device which cannot be opened unintentionally or by pressure that may arise within the package,

3. Containment penetrations must be protected against unauthorized operation and, except for relief valves, be protectively enclosed,

4. The containment system must not incorporate features that would permit continuous venting during transport.

4.2.2 Payload

The payload contains sufficient quantities of plutonium to warrant the special requirements of 10 CFR 71.63 ("Special Requirements for Plutonium Shipments").

4.2.3 Package Requirements Under Normal Transport Conditions

Under NCT (i.e., 10 CFR 71.71), supplemented by the requirements of 10 CFR 71.51(a)(1) and ANSI N14.5-1987, the package will not have any loss or dispersal of the radioactive contents to a sensitivity of 10^{-6} A_2 per hour.

4.2.4 Package Requirements Under Hypothetical Accident Conditions

Under HAC (i.e., 10 CFR 71.73), supplemented by the requirements of 10 CFR 71.51(a)(2) and ANSI N14.5-1987, the package will not have any:

1. Escape of krypton-85 exceeding 10 A_2 in one week,

2. Escape of other radioactive material exceeding a total of one A_2 in one week.

4.3 Review Procedures

The RTG package is designed with two nested containment vessels which provide double containment of the radioactive contents. Each of the two containment vessels is an independent containment boundary, which consists of a bell, a base, two elastomeric O-ring seals, an electrical feed-through assembly, and one (for the OCV) or two (for the ICV) vent port plugs with elastomeric O-ring seals. (See Figures 4.1.1-1 and 4.1.1-2 and Figures 4.1.2-1 to 4.1.2-5 in the RTG SARP; also see below.) Both containment vessels are sealed between their respective flanges and bases by a pair of face-sealing butyl O-rings. The inner butyl O-ring is the containment seal; the outer butyl O-ring is used for leakage rate testing purposes. The two containment vessels meet the double containment requirements of 10 CFR 71.63(b).

As noted above, each of the containment vessels is equipped with an electrical feed-through assembly. The purpose of the electrical feed-through assemblies is to provide a means to continuously monitor the RTG payload during transport. Each of these assemblies consists of an AISI Type 316L stainless steel body and sleeve, electrical conductor pins, and a glass sealing material between the body and pins. The electrical feed-through assemblies for the ICV and the OCV are mounted within recessed holes in their respective base plates, and they are sealed to their respective base plates with 3/16-in. fillet weld. Inside the ICV and outside the OCV, removable cables are used to connect the electrical feed-through assemblies to the RTG-mounted thermocouples and to the recording devices, respectively. Permanent wire connections are used in conjunction with spring-loaded pin contact assemblies to complete the electrical feed-through circuit between the two vessels. (See Figure 4.1.2-3 to 4.1.2-5 in the RTG SARP.)

As part of the assembly process, the ICV base plate is mounted to the OCV base plate. The ICV bell is mounted to its base plate and the OCV bell is mounted to its base plate. The nested pair of containment vessels is then lifted into, and bolted into, the impact limiter. With the installation of a tamper-indicating device over the top of one of the impact limiter attachment hole tubes (see Section 7.1.6 of the RTG SARP), the RTG package meets all of the requirements of 10 CFR 71.43.

For NCT and HAC, the applicant has shown that the requirements of 10 CFR 71.51(a)(1) and 10 CFR 71.51(a)(2) have been satisfied with the adoption of the ANSI N14.5-1987 definition of "leaktight" for the maximum allowable leakage rate from both RTG containment vessels. The ANSI N14.5-1987 definition of "leaktight" is equivalent to a Reference Air Leakage Rate of 0 when the sensitivity is 1.0×10^{-7} std cc/sec. For NCT and HAC, the applicant has shown that the requirements of 10 CFR 71.71 and 10 CFR 71.73 have been satisfied by a combination of testing, analysis, and reasoned argument. The Free Drop requirements of 10 CFR 71.71 and 10 CFR 71.73 and the Puncture test requirement of 10 CFR 71.73 were satisfied by the applicant by testing. After an extensive series of drop tests, both of the RTG containment vessels were helium leak-tested to verify that the total integrated leakage rate from each independent containment vessel was less than 1.0×10^{-7} std cm^3/sec (air). All leakage testing was performed in accordance with the requirements of ANSI N14.5-1987, and the minimum sensitivity for all leakage tests was demonstrated to be 5×10^{-8} std cc/sec or smaller.

The Heat and Cold requirements of 10 CFR 71.71 and the Thermal requirements of 10 CFR 71.73 were satisfied by the applicant through a combination of scale-model testing and reasoned argument. A scale-model test fixture was built for testing of the butyl O-rings at specific temperatures to demonstrate that the RTG O-ring temperature and compression limits will be maintained under all NCT and HAC. The fixture was placed in an environmental test chamber and brought to uniform temperatures for specified times. These tests consisted of an initial low temperature segment at -40° F, followed by a 380° F segment for 24 hours, then continuing at 350° F for 144 hours, followed by a final low-temperature segment at -20° F. After initial assembly, and at the end of each low-temperature segment, the O-rings were tested for "leaktight" conditions using standard helium mass spectrometer leakage rate testing equipment. At the end of each high-temperature segment, a vacuum test was performed using the mass spectrometer to achieve a pressure low enough to perform a test (less than 0.2 mbar).

As a follow-up to these tests, reasoned argument was then used to demonstrate that, as long as the temperature and compression limits for the O-rings were maintained for all NCT and HAC, the total integrated leakage rate from both containment vessels would be maintained at a rate less than 1.0×10^{-7} std cm^3/sec (air). Further support for the reasoned argument was based on post-test, cross-sectional diameter measurements of the O-rings. Information provided by the applicant states that only minor changes in the durometer (i.e., hardness) were noted, and the O-rings took on a compression set. (See Sections 4.1.3 and 2.10.6-1 of the RTG SARP.) Confirmatory analyses performed by the EM-76 Packaging Certification Team suggest that the temperature cycling measurements performed on the RTG O-rings were complete, accurate, and conservative.

The leakage rate testing performed after the drop tests was witnessed by EM-76 Packaging Certification Team. The Team has determined that the leakage testing results were sufficient to demonstrate that the RTG package satisfies the standard leakage rate acceptance criteria.

4.4 Findings and Conclusions

The full-scale testing, scale-model testing, and analytical results for containment provided by the applicant, as confirmed by the Packaging Certification Team, demonstrate that the package design meets the applicable requirements for containment specified in 10 CFR Part 71 (1983) and ANSI N14.5-1987, as defined in Section 4.2 (Acceptance Criteria) of this report. Chapter 4 of the RTG SARP also demonstrates compliance with 10 CFR Part 71 (1996) and IAEA Safety Series No. 6 (1985 Version, as amended in 1990).

Chapter 5. Shielding Evaluation

5.1 Areas of Review

Chapter 5 of the RTG SARP was reviewed for adequacy of the shielding design and analysis of the GPHS-RTG packaging. Included in the review were the following:

1. Shielding design features and design criteria,

    - Design features,
    - Design criteria,

2. Source specification,

   - Gamma source,
   - Neutron source,

3. Model specification,

   - Configuration of shielding and source,
   - Material properties,

4. Shielding analyses,

   - Computer programs,
   - Flux-to-dose-rate conversion,
   - Dose rates,

5. Supporting information or documentation.

5.2 Acceptance Criteria

5.2.1 Normal Transport Conditions

For NCT, the radiation levels external to the package must satisfy the conditions of §71.47, §71.43(f), and §71.51(a)(1), which are:

1. 1,000 mrem/h on the surface of the package,

2. 200 mrem/h on the surface of the vehicle,

3. 10 mrem/h at a distance of 2 m from the vehicle,

4. 2 mrem/h in normally occupied areas, unless the occupant wears radiation dosimetry devices in accordance with 10 CFR 20.1502.

5.2.2 Hypothetical Accident Conditions

For HAC, the radiation levels external to the package must satisfy the condition of §71.51(a)(2), which is 1 rem/h at a distance of 1 m from the package.

5.3 Review Procedures

5.3.1 Shielding Design Features and Design Criteria

The RTG package contains no special design features for shielding. Other packaging features, such as the inner and outer steel containment vessels, as well as the outer shell of the RTG and the RTG itself, do provide some attenuation of neutron and gamma radiation.

The RTG package was designed and analyzed for exclusive-use shipment of one GPHS RTG in a closed semi-trailer in accordance with the applicable acceptance criteria defined in Section 5.2 above. (The shielding requirements for the RTG are the same in the 1983 and 1996 versions of 10 CFR 71.) As discussed in Chapter 1 of the RTG SARP, a water cooling system is implemented during transport to maintain the RTG at acceptable temperatures for follow-on operational use, but this cooling system is not required to satisfy regulatory transport criteria. Although the presence of water in the coolant channels will provide some shielding (primarily of neutrons), no credit for this shielding is taken in the shielding analysis. Furthermore, because pre-shipment measurements (discussed in more detail in Chapter 7 of the RTG SARP) will be performed with water in the coolant channels, operational control limits have been established to ensure that allowable external radiation levels will not be exceeded even if the water is not present. The operational control limits are discussed in Section 5.3.4 below.

5.3.2 Source Specification

Section 1.2.3 of the RTG SARP specifies the allowed contents for the GPHS RTG. Additional detail is provided in Section 5.2. The primary radiation source is neutron radiation from the spontaneous fission of ^{238}Pu and from α-n reactions with ^{17}O and ^{18}O. Additional external radiation results from gamma radiation, primarily from the daughters of ^{236}Pu, which is present at less than 1 ppm of total Pu.

As discussed in Section 5.2 of the RTG SARP and supporting documentation presented during the review, determination of the neutron source term is based on the specification that the GPHS could not exceed 6,000 n/s/g of ^{238}Pu at time of production. Based on the maximum allowed concentration of 86% ^{238}Pu and a maximum content of 157 grams of PuO_2 per fueled clad, a total neutron source strength of 7.13 x 10^5 n/s per fueled clad was calculated. No credit was taken for decay of the Pu since the time of production. The neutron source from spontaneous fission was calculated (based on the inventory of allowable actinide nuclides) to be 2.77 x 10^5 n/s per clad; the remainder of the neutron source, 4.36 x 10^5 n/s per clad, was attributed to α-n reactions. Table 5-5 of the RTG SARP presents a detailed neutron source term by energy group. The Packaging Certification Team accepted the total neutron source term based on the production specification and confirmed the spontaneous fission contribution by both ORIGEN2 [see ORNL CCC-371A] and hand calculations.

The RTG SARP contained an estimate of the gamma source term due to decay of allowable radionuclides in the GPHS for 17.5 years, the time of the maximum source strength. The Packaging Certification Team concurs with the gamma source term based on ORIGEN2 and MicroShield calculations [Grove Engineering, Inc., 1992].

5.3.3 Model Specification

The model for the shielding analysis of the RTG under normal conditions of transport was described in Section 5.3 of the RTG SARP. The model included each of the 72 oxide pellets, their iridium cladding and graphite aeroshells, the RTG outer shell, the inner and outer containment vessels, and the water coolant. (As discussed in Section 5.3.4 below, dose rates were calculated both with and without the water present.) The quartz insulation, thermopile assembly, and conveyance structure were conservatively ignored. The model also included the ground in the vicinity of the semi-trailer to account for scattering of neutron and gamma radiation. Material compositions are described in Table 5-8 of the RTG SARP, and model descriptions are presented in Figures 5-3 and 5-4.

The model for hypothetical accident conditions was conservatively assumed to be a sphere consisting of PuO_2 only, placed against the inner containment vessel at the top of the package (where the shielding is at a minimum). As described in Chapter 2 of the RTG SARP, the package itself was shown to remain intact under hypothetical accident conditions. Material compositions are described in Table 5-9, and model descriptions are presented in Figure 5-5.

5.3.4 Shielding Analyses

RTG SARP calculations of the dose rates for the RTG were performed with MCNP [Briesmeister, 1993]. Neutron and photon fluxes were determined at the appropriate locations, and dose rates were computed using the flux-to-dose-rate conversion factors of ANSI/ANS 6.1.1-1977. Approximate dose rates under normal conditions of transport, presented in Tables 5-1 and 5-1a of the RTG SARP, are summarized in table 5-1 below.

Table 5-1. Summary of Maximum Dose Rates and Operational Control Limits (mrem/h) for Normal Conditions of Transport

Location	Dose Rate (with out water)	Dose Rate (with water)	Regulatory Limit	Operational Control Limit
Side surface of package	305.	184.	1,000.	590.
Side surface of semi-trailer	52.1	33.2	200.	120.
Two meters from side of semi-trailer	9.	5.76	10.	6.4
Top surface of package	201.	210.	1,000.	1,000.
Top surface of semi-trailer	46.2	47.9	200.	200.
Bottom surface of semi-trailer	15.	14.4	200.	190.
Tractor cab (operator's seat)	1.59	1.01	2.	1.2

The dose rates without water are generally significantly less than the regulatory limits. The regulatory limit for the tractor operator is not applicable for private carriers if the operator wears radiation dosimetry devices in conformance with 10 CFR 20.1502. The dose rate at a distance of two meters from the side of the semi-trailer was determined to be approximately 9.0 mrem/h. Pre-shipment measurements, discussed in Chapter 7 of the SER, will verify that the regulatory limits are not exceeded.

As discussed in Section 5.3.1 above, although no credit is taken for the water coolant in satisfying the regulatory criteria for external radiation, water will be present during the pre-shipment measurements. The operational control limits shown in the above table account for the attenuation of radiation due to the water presence, and represent the actual radiation levels that cannot be exceeded in the pre-shipment measurements. For example, the dose rate at two meters from the side of the vehicle was calculated to be 5.76 and 9.0 mrem/h with and without water, respectively. The operational control limit is therefore 5.76/9.0 times 10 (the regulatory limit), or 6.4 mrem/h.

The dose rate under HAC at one meter from the top surface of the package was determined to be approximately 133 mrem/h, significantly less than the regulatory limit of 1 rem/h (1,000 mrem/h).

Confirmatory analysis by the Packaging Certification Team consisted of detailed verification of the shielding models and input files, confirmation of the flux-to-dose-rate conversion factors, and comparison of dose rates with independent analyses and measurements presented as supporting documentation. The notes that the source terms are somewhat conservative. The neutron source was considered to be that at the time of production, while the gamma source was that after a decay time of 17.5 years. Additional conservatism is provided by neglecting RTG and semi-trailer structural features. Final confirmation of the dose rates will be provided by pre-shipment measurements, which cannot exceed the operational control limits.

5.3.5 Supporting Information or Documentation

MCNP input files for gamma and neutron shielding analysis were presented in Sections 5.5.2 and 5.5.3 of the RTG SARP, respectively. In addition, several background documents on the development of the GPHS source term and independent analyses of dose rates were provided during the review process.

5.4 Findings and Conclusions

The applicant's shielding analyses, as confirmed by the Packaging Certification Team, demonstrate that the package design satisfies the applicable requirements for shielding in 10 CFR Part 71 (1983) as defined in Section 5.2 (Acceptance Criteria) of this report. The RTG SARP also demonstrated compliance with 10 CFR Part 71 (1996) and IAEA Safety Series No. 6 (1985 version, as amended in 1990).

Chapter 6. Criticality Evaluation

6.1 Areas of Review

Chapter 6 of the RTG SARP was reviewed for adequacy of the criticality design features and analysis of the RTG package. Included in the review were the following:

1. Criticality control design features and design criteria,
   - Design features,
   - Design criteria,
2. Package fuel loading,
3. Model specification,
   - Description of calculational model,
   - Package regional densities,

4. Criticality evaluation,

   - Calculational or experimental method,
   - Fuel/moderator loading optimization,
   - Criticality results,

5. Critical benchmark experiments,

   - Benchmark experiments and applicability,
   - Details of benchmark calculations,
   - Results of benchmark calculations,

6. Supporting information or documentation.

6.2 Acceptance Criteria

A package exempt from fissile material classification and fissile material standards of §§71.55 through 71.61 must satisfy the requirements of §71.53. A package used for the shipment of fissile material must satisfy the requirements of §§71.41 through 71.47 and §71.51 (Type B).

Unless exempted by §71.55(c), a package used for the shipment of fissile material must satisfy the requirements of §71.55(b).

Under NCT, a package used for the shipment of fissile material must satisfy the requirements of §71.55(d) and either §71.57(a), §71.59(a), or §71.61(a).

Under HAC, a package used for the shipment of fissile material must satisfy the requirements of §71.55(e) and either §71.57(b), §71.59(b), or §71.61(b).

6.3 Review Procedures

6.3.1 Criticality Control Design Features and Design Criteria

The GPHS RTG package is described in Section 1.2 and 6.3 of the RTG SARP. The package contains no special criticality control features. The package is intended to be shipped as Fissile Class III, with one package per shipment. The applicable design criteria for criticality specified in the RTG SARP are §71.55(b), §71.55(d), and §71.61(a) for normal conditions of transport, and §71.55(e) and §71.61(b) for hypothetical accident conditions.

In accordance with 10 CFR Part 71 (1983), for a Fissile Class III package with one package per shipment, two undamaged packages must be shown to be subcritical if stacked together in any arrangement and reflected by water on all sides of the stack. One package, considered to have been subjected to the HAC tests of §71.73, must be shown to be subcritical when closely reflected by water. This latter criterion is bounded by the requirements of §71.55(b) for water inleakage of a single package. The requirements of 10 CFR Part 71 (1996) for a one-package shipment are similar, except that three undamaged packages must be demonstrated to be subcritical. As discussed in Section 6.3.4 below, although the two-package analysis demonstrated a substantial margin of safety, no analysis was performed for three packages. Consequently, the RTG SARP does not demonstrate that the GPHS RTG satisfies §71.59(a)(1) of 10 CFR Part 71 (1996). An appropriate criticality transport index, based on 10 CFR Part 71 (1996), is provided in Section 6.4.

6.3.2 Package Fuel Loading

The maximum fuel loading is indicated in Table 6.2-1 of the RTG SARP. The GPHS RTG can contain a maximum of 11.3 kg of PuO_2, with the ^{238}Pu content between 80% and 86% of the total Pu. Criticality analyses considered both an 80% and 86% loading, with the remainder considered to be ^{239}Pu. The most reactive cases were those in which the ^{238}Pu content was 80% (^{239}Pu content was 20%).

6.3.3 Model Specification

Model specifications for the GPHS RTG are described in Section 6.3.1 of the RTG SARP. The primary configurations on which the criticality assessments were based were (1) two RTGs in close contact with each other and fully reflected by water and (2) one RTG consisting of a 4x4x5 array of fueled clads (conservatively evaluated without iridium cladding), with optimal moderation and spacing, and full reflection. Table 6.4.3-1 and Figures 6.3.1-2 through 6.3.1-13 of the RTG SARP describe additional configurations to support the conclusion that the package satisfies the acceptance criteria.
Table 6.3.2 of the RTG SARP provides package regional densities used in the models.

6.3.4 Criticality Evaluation

Criticality calculations, performed with MCNP-4A [Briesmeister, 1993], are discussed in Section 6.4 of the RTG SARP. Cross-sections were either those from ENDFB-V or a Los Alamos evaluation, as depicted in the input files presented in Section 6.6.2 of the RTG SARP.

A summary of the results of the criticality evaluation, presented in Table 6-1 and Table 6.4.3-1 of the RTG SARP, is depicted in the table below. Confirmatory analyses by the Packaging Certification Team using MCNP with ENDFB-V cross-sections, including an $S(\alpha,\beta)$ treatment of the water, were in essential agreement with those presented in the RTG SARP.

Table 6-1. Summary of Criticality Analyses
(all cases reflected by 30 cm of water)

Case	$k \pm \sigma$
GPHS RTG (NCT)	
One RTG	0.404 ± 0.003
Two RTGs	0.409 ± 0.002
GPHS RTG (HAC)	
4x4x5 array of clads	0.745 ± 0.004

6.3.5 Critical Benchmark Experiments

Three critical benchmark experiments were analyzed and the results discussed in Section 6.5 of the RTG SARP. These benchmarks included two ^{239}Pu metal sphere experiments and one with unreflected cylinders of UO_2F_2 enriched to 93.2% ^{235}U. Although each of these benchmarks tested MCNP's ability to calculate k_{eff} accurately, none was a thorough test for the plutonium oxide, especially of the cross-sections for ^{238}Pu (for which no critical benchmark experiments exist). As shown in the table above, the criticality calculations for the GPHS RTG indicate that it is significantly subcritical. Section 6.5.3 of the RTG SARP presented additional analyses and justification to show that credible uncertainties in the ^{238}Pu cross-sections would not alter the conclusion that the RTG remained significantly subcritical. The Packaging Certification Team concurs.

6.3.6 Supporting Information or Documentation

Reference 5 of RTG SARP Chapter 6 was provided as supporting documentation for the PuO_2 density for the GPHS RTG Package.

6.4 Findings and Conclusions

The applicant's criticality analyses, as confirmed by the Packaging Certification Team, demonstrate that the package design satisfies the applicable requirements for criticality in 10 CFR Part 71 (1983), as defined in Section 6.2 (Acceptance Criteria) of this report, for a Fissile Class III package with one package per shipment.

Demonstration that the package satisfies the criticality requirements of 10 CFR Part 71 (1996), §71.59(a)(1) was not presented in the RTG SARP. Consistent with accepted practices of both the DOE and NRC for packages approved under 10 CFR Part 71 (1983), a criticality transport index of 100 shall be assigned to the GPHS RTG.

Because the criticality requirements of 10 CFR Part 71 (1996) are equivalent to those of the 1985 IAEA Safety Series No. 6 (as amended in 1990), the RTG SARP likewise does not demonstrate that the requirements of the latter have been satisfied.

Chapter 7. Operating Procedures

7.1 Areas of Review

Chapter 7 of the RTG SARP was reviewed for adequacy of the operating procedures required for the use of the RTG package. Included in the review were the following:

1. The generic guidance for the preparation of operating procedures established in Reg. Guide 7.9 suggests that the following information should be included in the RTG SARP:

   - Procedures for loading the package,
   - Procedures for unloading the package,
   - Preparation of an empty package for shipment,
   - The inclusion of appropriate appendices.

2. More specific guidance on the preparation of operating procedures in NUREG/CR-4775 suggests that the operating procedures chapter should also include, as a minimum, appropriate discussions of the following:

   - Operating requirements and restrictions,
   - General information,
   - Package loading,
   - Shipment preparation,
   - Package receipt,
   - Package unloading,
   - Inspection and maintenance,
   - Records and reporting requirements.

7.2 Acceptance Criteria

With respect to operating procedures, 10 CFR Part 71 states two clear requirements for a SARP:

1. §71.31 states that an application for an approval under 10 CFR Part 71 must include a package evaluation as required by §71.35. With respect to operating procedures for Fissile Class III shipment, §71.35 states that the application must include any proposed special controls and precautions for transport, loading, unloading, and handling, and any proposed special controls in the event of accident or delay.

2. In addition, §71.31 states that an application for an approval under 10 CFR Part 71 must include a description of a quality assurance program as required by §71.37, which in turn requires, in part, that an applicant describe the quality assurance program (per Subpart H of 10 CFR Part 71) for the use of the proposed package. With respect to operating procedures, Subpart H states in §71.111 that activities affecting quality shall be described by documented instructions, procedures, or drawings of a type appropriate to the circumstances.

In addition, 10 CFR Part 71 states requirements with respect to operating procedures for a package licensee, primarily in Subpart G. While these are stated as requirements to the licensee and not for the applicant, it is important that the applicant include discussion of some of these in the SARP. Further recommendations for operating procedures in the SARP are given by Reg. Guide 7.9:

1. Procedures for package loading,

2. Procedures for package unloading,

3. Preparation of empty package for transport.

7.2.1 Primary Regulations

The primary regulations that govern operating procedures can be located in the following:

1. DOE Order 460.1,

2. 10 CFR Part 71, Subpart G (Operating Controls and Procedures),

3. 10 CFR Part 71, Subpart H (Quality Assurance).

7.2.2 Additional Regulations

Additional regulations governing operating procedures can be found in the following:

1. 10 CFR 19.12 (Reporting Requirements for Radiation Exposures),

2. 10 CFR 20.1906 (Procedures for Receiving and Opening Packages),

3. 10 CFR 71.47 (External Radiation Standards for All Packages),

4. 49 CFR 173.428 (Empty Class 7 (Radioactive) Materials Packaging),

5. 49 CFR 173.443 (Contamination Control),

6. 49 CFR 173.475 (Quality Control Requirements Prior to Each Shipment of Class 7 (Radioactive) Materials).

7.3 Review Procedure

The operating procedures presented in the RTG SARP were reviewed by the Packaging Certification Team for completeness and compliance with regulatory requirements. The information provided by the applicant was in the format prescribed directly by Reg. Guide 7.9. Although no attempt was made to provide the information in the format outlined in NUREG/CR-4775, the applicable information on operating requirements, general information, package loading, shipment preparation, package receipt, and package unloading was provided in the operating procedures chapter. Work will be accomplished by using documented and approved procedures. Supplemental information on inspection and maintenance and on records and reporting requirements has been provided in Chapters 8 and 9 of the RTG SARP, respectively.

7.4 Findings and Conclusions

A review of the operating procedures provided by the applicant in Chapter 7 of the RTG SARP indicates that the operating procedures meet the requirements of 10 CFR Part 71 (1983), as outlined in Section 7.2 (Acceptance Criteria) of this report. Chapter 7 of the RTG SARP also demonstrated compliance with 10 CFR Part 71 (1996) and IAEA Safety Series No. 6 (1985 version, as amended in 1990).

Chapter 8. Acceptance Tests and Maintenance Program

8.1 Areas of Review

Chapter 8 of the RTG SARP was reviewed for adequacy of the acceptance tests and maintenance program associated with the RTG package. Included in the review were the following:

1. The primary areas of review for acceptance tests, as defined in Reg. Guide 7.9 are:

   - Visual inspections,
   - Structural and pressure tests,
   - Leakage tests,
   - Component tests,
   - Tests for shielding integrity,
   - Thermal acceptance tests.

2. The primary areas of review for the maintenance program, as defined in Reg. Guide 7.9 are:

   - Structural and pressure tests,
   - Leakage tests,
   - Subsystem maintenance,
   - Valves, gaskets, etc., on the containment vessel,
   - Shielding tests,
   - Thermal tests.

8.2 Acceptance Criteria

§71.85 states that, prior to the first use of any packaging:

1. There shall be no cracks, pinholes, uncontrolled voids, or other defects which could significantly reduce the effectiveness of the packaging.

2. Where the maximum normal operating pressure exceeds 34.3 kilopascal (5 psi) gauge, the containment system shall be tested at an internal pressure at least 50% higher than the maximum normal pressure to verify its ability to maintain structural integrity.

3. The packaging shall be conspicuously and durably marked with its proper model number, gross weight, and a package identification number.

4. Prior to applying the model number, the licensee shall determine that the packaging has been fabricated in accordance with the design approved by the Commission.

§71.87 states in part that, prior to each shipment, the licensee shall determine that:

1. The package is proper for the contents to be shipped.

2. The package is in unimpaired physical condition except for superficial defects such as marks or dents.

3. Each closure device of the packaging, including any required gasket, is properly installed and secured and free of defects.

4. The package has been loaded and closed in accordance with approved procedures.

5. Any structural part of the package which could be used to lift or tie down the package during transport is rendered inoperable for that purpose unless it satisfies the design requirements of 10 CFR 71.45.

8.3 Review Procedure

The packaging acceptance tests and maintenance program are deemed acceptable if it can be shown that they are in compliance with the appropriate requirements set forth above.

The information provided by the applicant for acceptance tests is in the format specified directly in Reg. Guide 7.9. The applicant has noted that visual inspections will be performed in accordance with specifications delineated in the package drawings found in Appendix 1.3.2 of the RTG SARP. Structural and pressure test requirements have been outlined for lifting device load testing, ICV and OCV pressure vessel testing, and OCV coolant jacket pressure testing. Leakage rate test procedures have been outlined for 1) the main ICV closure seal, 2) the primary ICV vent port plug seal, 3) the secondary ICV vent port plug seal, 4) the ICV structure (including the ICV electrical feed-through assembly), 5) the OCV structure (including the OCV electrical feed-through assembly), 6) the main OCV closure seal, and 7) the OCV vent port plug seal. Component testing procedures have been outlined for the polyurethane foam and the O-ring seals and seal material. The applicant has noted that, because the materials and the design requirements specified for the ICV and the OCV were selected to provide adequate shielding, no additional shielding tests are required for acceptance testing. The applicant has also noted that, with the exception of the polyurethane foam fire retardancy tests discussed in Section 8.1.4 of the RTG SARP, no additional thermal tests are required for the RTG for acceptance testing.

The information provided by the applicant for the maintenance program is also in the format specified directly in Reg. Guide 7.9. Discussions have been provided by the applicant on structural and pressure tests and on leakage rate testing of 1) the main ICV closure seal, 2) the primary ICV vent port plug seal, 3) the secondary ICV vent port plug seal, 4) the main OCV closure seal, and 5) the OCV vent port plug seal. Discussions have also been provided on subsystems maintenance, including fasteners, seal areas and grooves, on painted surfaces, and on valves, rupture discs, and gaskets on the containment vessel. As was noted in the acceptance tests description above, the applicant has noted that no additional shielding inspections or tests are required as part of the maintenance program to ensure the continued satisfactory performance of the RTG. For thermal testing, the applicant has noted that, although no thermal testing is required as part of the maintenance program to ensure the continued satisfactory performance of the RTG, visual inspections of the thermal insulation located on the bottom of the payload shipping rack will be required at least on an annual basis. Periodic leakage testing of the ICV and OCV containment boundaries and feed-through assemblies will be performed as part of the maintenance program. This information is not in the SARP. It will, therefore, be added as a requirement in the Certificate of Compliance.

8.4 Findings and Conclusions

The descriptions of the acceptance tests and maintenance programs for the RTG package were reviewed and found to meet the requirements of 10 CFR Part 71 (1983), as outlined in Section 8.2 (Acceptance Criteria) of this report. Chapter 8 of the RTG SARP also demonstrates compliance with 10 CFR Part 71 (1996) and IAEA Safety Series No. 6 (1985 Version, as amended in 1990).

Chapter 9. Quality Assurance

9.1 Areas of Review

The RTG Chapter 9 was reviewed for adequacy of the proposed quality assurance program for the RTG package. Included in this review were the following sections:

1. Introduction (9.1),
2. Scope (9.2),
3. Quality Assurance Plan (9.3),
4. References (9.4).

9.2 Acceptance Criteria

10 CFR 71.31 states that an application for an approval under 10 CFR Part 71 must include a description of a quality assurance program as required by §71.37. 10 CFR 71.37 states:

1. The applicant shall describe the quality assurance program (per Subpart H of 10 CFR Part 71) for the design, fabrication, assembly, testing, maintenance, repair, modification, and use of the proposed package.

2. The applicant shall identify any established codes and standards proposed for use in package design, fabrication, assembly, testing, maintenance, and use. In the absence of any codes and standards, the applicant shall describe the basis and rationale used to formulate the package quality assurance.

3. The applicant shall identify any specific provisions of the quality assurance program which are applicable to the particular package design under consideration, including a description of the leak-testing procedures.

10 CFR Part 71 Subpart H describes the required 18-element quality assurance program which is similar to, but less detailed than, ASME NQA-1-1989, but has been specifically tailored for work relating to the transportation of radioactive materials.

9.3 Review Procedure

The applicant's quality assurance chapter states that this package must meet the requirements of several documents including: DOE Order 5700.6C, 10 CFR 830.120, and 10 CFR Part 71 Subpart H. The described RTG quality assurance program is capable of satisfying the above requirements when properly implemented.

The quality assurance elements included in the "Quality Assurance Plan," Section 9.3, include all of the required subject material identified in the above referenced documents. The incorporation of the graded approach, as identified in DOE Order 5700.6C and Reg. Guide 7.10, is evident by the establishment of the quality assurance categories A, B, and C, and the further identification of the respective components and subcomponents in Table 9.3.2-1, "Quality Assurance Levels for Design and Procurement of RTG Package Components," as one of these three categories.

The requirements of the WHC QA manual WHC-CM-4.2, "Quality Assurance Manual," apply to the RTG program and require that a quality assurance plan be developed for each project. The quality assurance requirements for the RTG project are described in the quality assurance program plan document WHC-SD-RTG-QAPP-001. Attachment 1 of this document consists of a matrix relating the contents of the requirements documents (10 CFR Part 71 Subpart H, and 10 CFR 830.120, which is essentially the same as 5700.6C) to a large number of detailed WHC implementing procedures, which are used at WHC operations to the extent appropriate for the type of work being performed.

Work will be accomplished by using documented approved instructions, procedures, and drawings. Special processes including nondestructive examination, chemical analysis, metal finishing and coatings, heat treating, and cleaning will be controlled through the use of approved procedures and by the use of qualified or certified personnel.

9.4 Findings and Conclusions

The RTG SARP meets the requirements of 10 CFR Part 71 (1983) Subpart H and 10 CFR 71 (1996) Subpart H. In addition, the RTG transportation system package quality assurance program description in the RTG SARP, which has been prepared by WHC, meets the requirements of ASME NQA-1-1989, 10 CFR Part 830.120, and DOE Order 5700.6C. The described WHC RTG quality assurance program meets the IAEA Safety Series No. 6 (1985 version, as amended in 1990) requirements.

Approved:

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Office of Transportation, Emergency Management and Analytical Services, EM-76

Date: MAY 31 1996

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